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SOLAR CELL MODULES
FOR
PLASMA INTERACTION EVALUATION

FINAL REPORT

NAS8-34026

Prepared for

National Aeronautics & Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama

LOCKHEED MISSILES & SPACE COMPANY, INC.

FOREWORD

This report documents the work performed on the Solar Cell Modules for Plasma Interaction Evaluation project by Lockheed Missiles & Space Company, Inc., Sunnyvale, California, for Marshall Space Flight Center of the National Aeronautics and Space Administration under contract no. NAS8-34026.

This report summarizes the full term effort performed on the subject contract over the period 29 July 1980 to 31 July 1981. The outcome of this project was two 36-cell modules which will be tested in a plasma chamber to investigate current loss mechanisms. L. E. Young of the Astrionics Laboratory, Power Systems Branch of NASA/MSFC, provided technical direction for this work.

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1.0 INTRODUCTION

The Solar Electric Propulsion Subsystem (SEPS) has been proposed as the basic propulsion module for future NASA interplanetary missions. Several studies have suggested the possibility of a significant power loss occurring due to collection of charged particles on the solar array interconnects which are biased to a high potential relative to the plasma. Under this contract, two solar array segments were designed and built to allow an experimental investigation of those design parameters which affect the collection of plasma particles.

The term of the basic contract was six months, beginning on 29 July 1980 and concluding 31 January 1981. Due to difficulties in obtaining the specified type of solar cell from the vendors, several contract extensions were required until cells finally became available in mid-June 1981. Both modules were shipped during the week of 31 July 1981.

2.0 PLASMA INTERACTION ANALYSIS

2.1 BASELINE SEPS DESIGN

Since the SEPS vehicle configuration has not been fully specified, a model spacecraft was synthesized from various design options mentioned in the literature. The SEPS solar array subsystem chosen is composed of two wings with each wing 5.5 m wide by 33 m long. The centerline of the array is located 2.2 m upstream of the ion thruster exhaust plane. Located on opposite sides of the vehicle, the two array wings are positioned with the inboard edges 3.8 m from the centerline. Array voltage distribution is assumed to be a repeating pattern ranging from 0 volts to some maximum (V_{max}) over a 0.75 m distance. Ten 30 cm mercury ion thrusters operating at a beam current of up to 2 amps each was chosen as the propulsion stage. Maximum power loss is expected when the array is oriented with the surface normal perpendicular to the vehicle centerline.

2.2 ION THRUSTER PLUME MODEL

In order to calculate the plasma environment surrounding the solar arrays, a model of the charge exchange plasma developed by Kaufman, et al (Reference 1) was utilized. Using this model, the plasma density of a single thruster can be expressed as:

$$Ne \quad \alpha \quad J_B^2 \quad \left(\frac{1-\eta}{\eta}\right) \tag{1}$$

where

J_B = Beam Current

η = Fuel Utilization

For multiple thruster applications, plasma density can be assumed to scale either directly with the number of thrusters

$$Ne \quad \alpha \quad n\,J_B^2 \quad \left(\frac{1-\eta}{\eta}\right) \tag{2}$$

n = number of operating thrusters

or through scaling of the beam current

$$Ne \; \alpha \; (n\, J_B)^2 \; \frac{(1 - \eta)}{\eta} \tag{3}$$

Scaling the density directly by the number of thrusters (Eq. 2) contains an implicit assumption that the thrusters are spaced sufficiently far apart to minimize interactive effects. Scaling the beam current (Eq. 3) allows for maximum beam interaction, effectively treating the multiple thruster case as one giant thruster. Future experimental work should attempt to determine the magnitude of thruster interactions.

Figures 2-1 and 2-2 show the results for calculations of two different operational conditions. These figures show quite clearly that the plasma current density varies strongly as a function of position on the array and thruster model.

2.3 PLASMA/SOLAR ARRAY INTERACTION

The amount of current collected by an array is highly voltage dependent. During a previous experimental study of plasma interactions with a Lockheed flexible solar array segment, three different collection mechanisms were postulated to explain the experimental data:

1) Collection proportional to exposed conductor area at low voltage
2) Orbit limited current collection at intermediate voltages
3) Sheath limited current collection at high voltages

These three processes are shown in Figure 2-3. A simple theoretical model based on these assumed processes was developed to explain the test results. A comparison of test data and model predictions is shown in Figure 2-4. This figure shows that the current collection over the voltage range of interest for SEPS is dominated by contributions from the sheath limited $V^{3/2}$ term.

Along with the assumption of sheath limited current, this study assumes a planar geometry for the sheath and neglects effects due to sheath curvature. This omission introduces an error proportional to the ratio of edge area to frontal area:

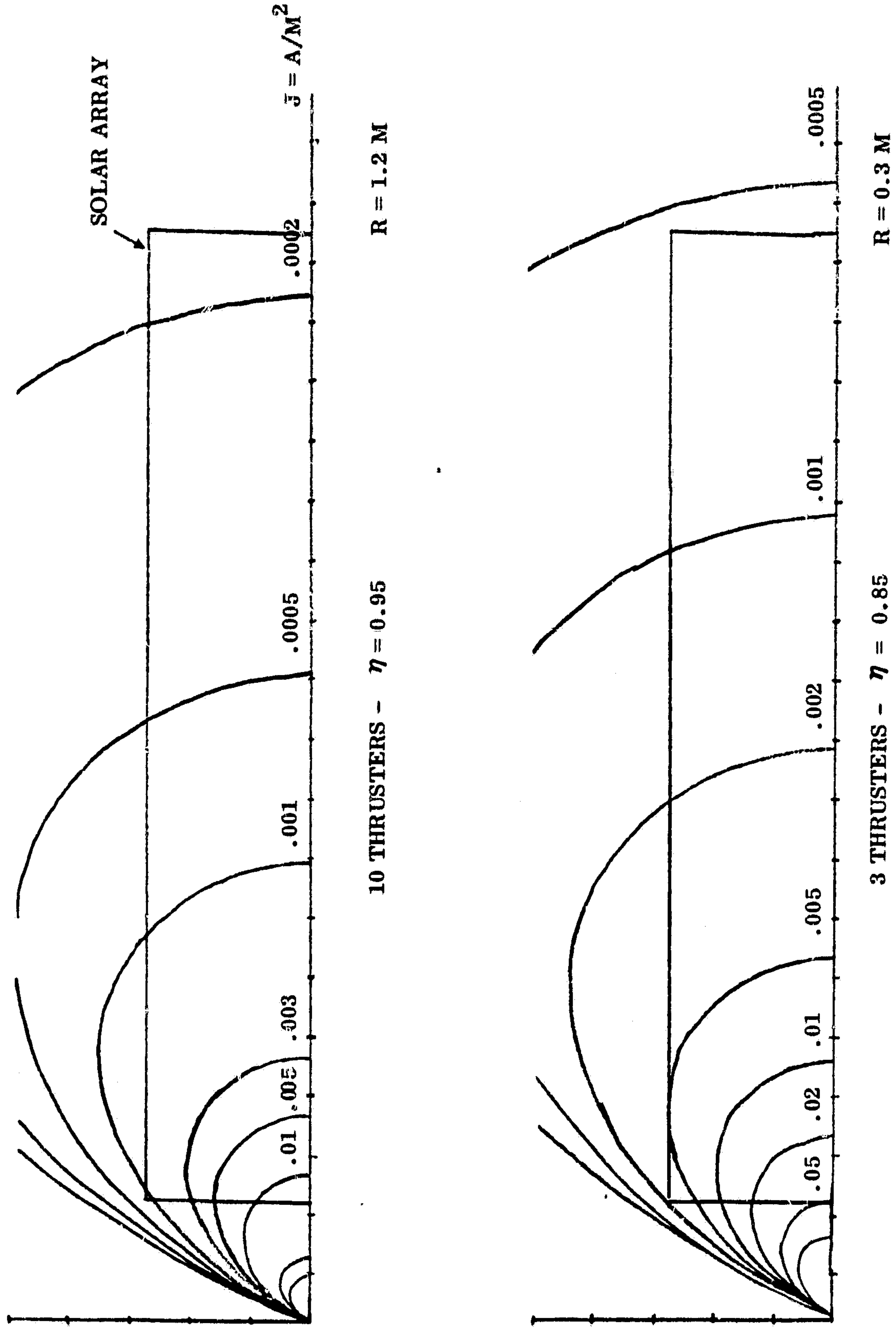


Figure 2-1 Current Density Plots - SEPS Array - Non-Interacting

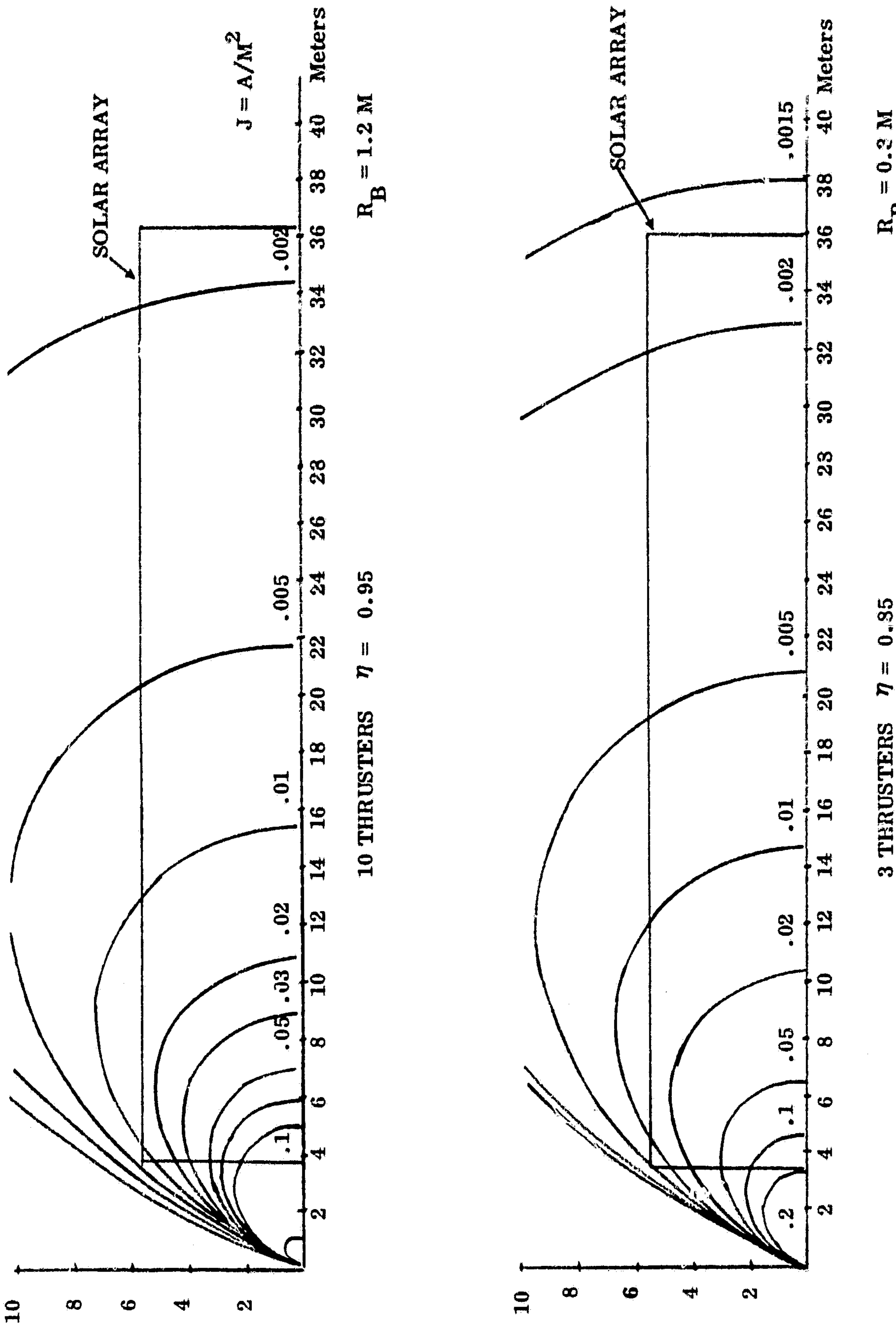


Figure 2-2 Current Density Plots - SEPS Array - Interacting

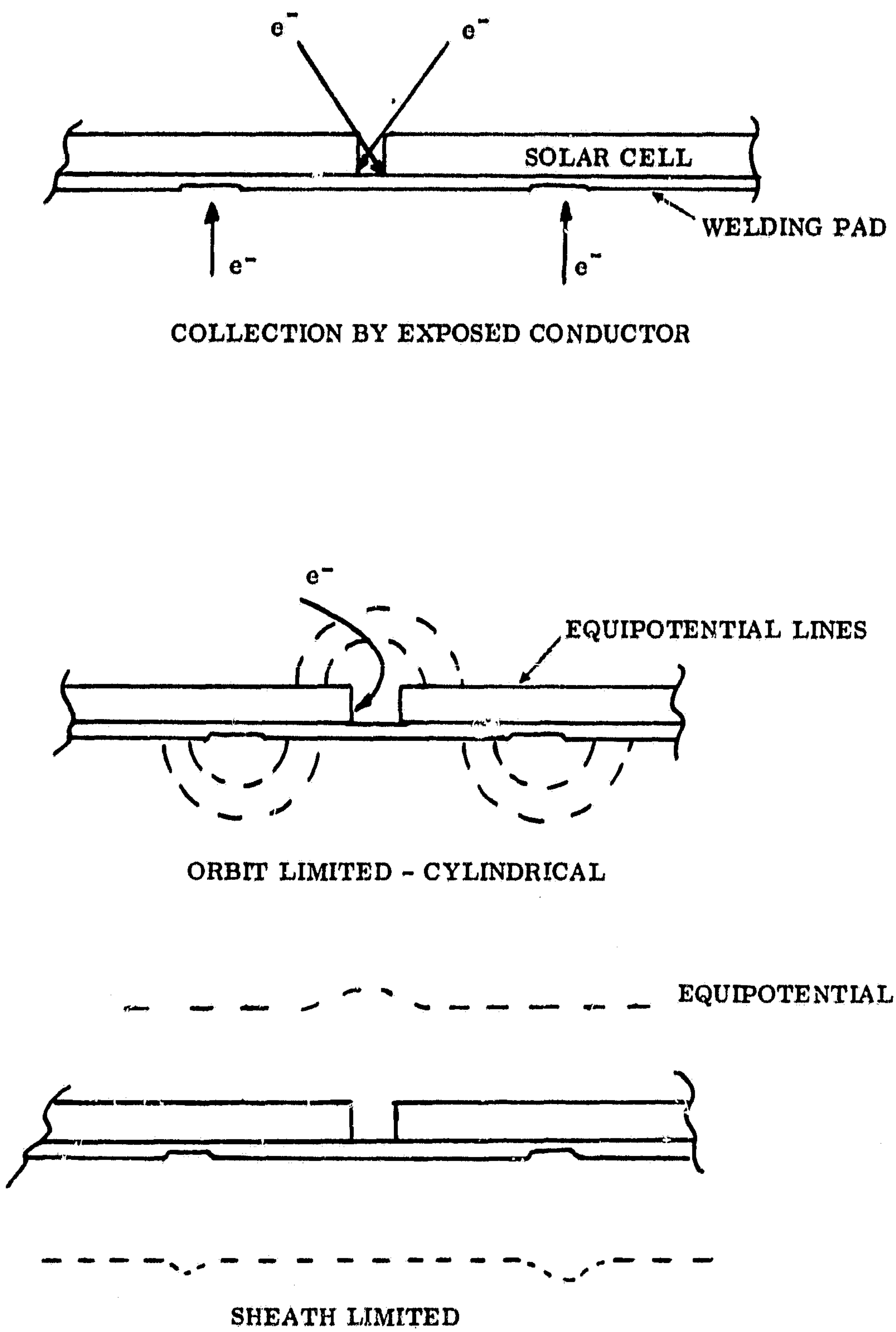


Figure 2-3 Major Plasma Collection Mechanisms

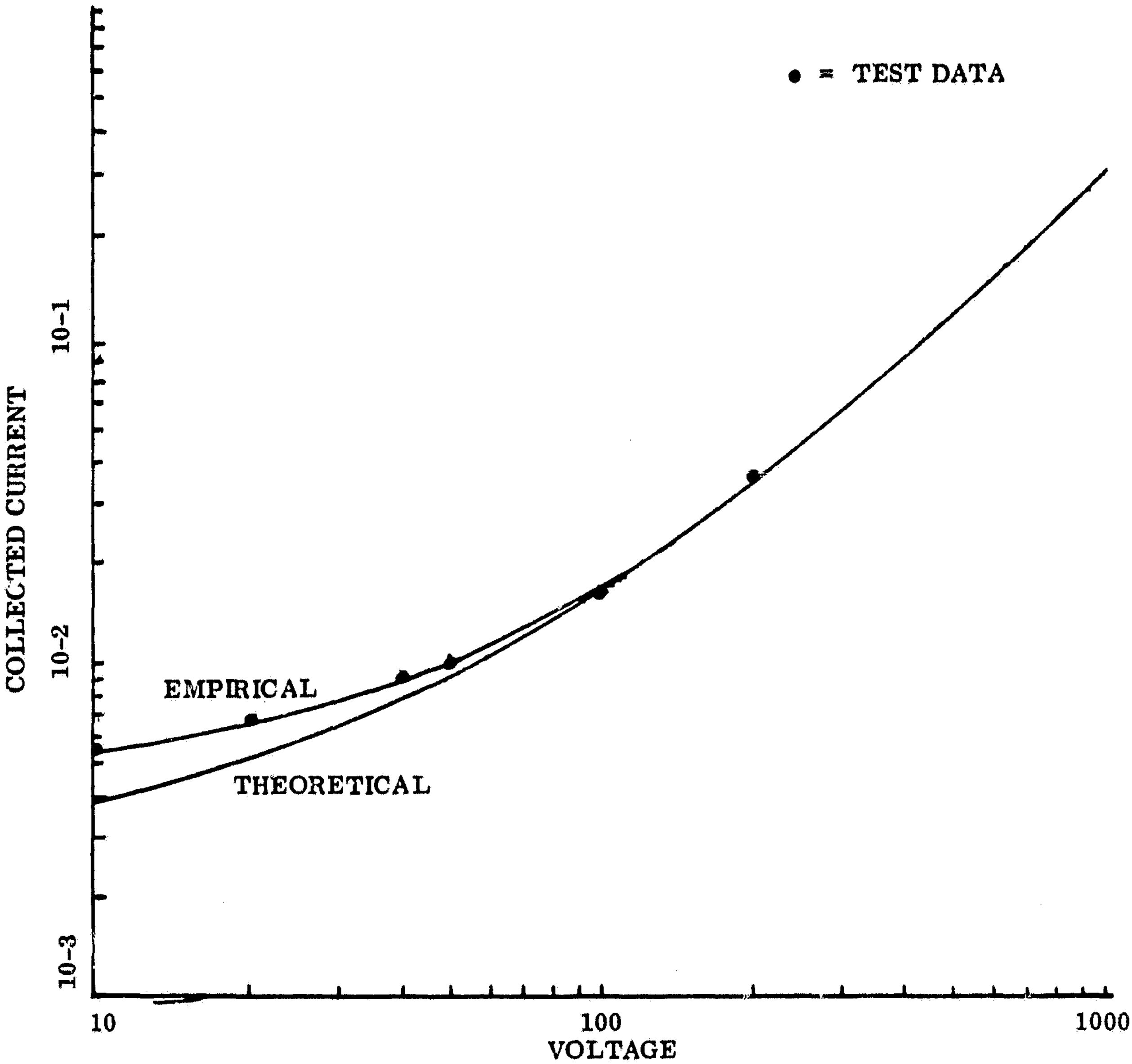


Figure 2-4 LMSC Flexible Solar Array Test/Analysis Results

$$\text{Effective Area} \approx \left(1 + \frac{2\pi D}{W}\right) W L \tag{4}$$

D = Sheath Thickness
W = Array Width
L = Array Length

For the SEPS array, the sheath thickness varies with position on the array, ranging from $0.2 < D < 2.0$ m (Figure 2-5) leading to an error between 4% and 36%. Future studies should attempt to accurately model the sheath boundary.

The rate at which work is done in accelerating a charged particle during the transit period from sheath boundary to array impact constitutes a power loss. Other studies have assumed the effective array voltage for current collection is the average panel voltage. Implicit within this approach is the assumption that the particle trajectories are straight lines through the sheath which are not influenced by the potential distribution on the array. Trajectories will show little curvature if the rates of the component of force parallel to the array to the normal component is small. This condition, when applied to a solar array, implies that

$$\frac{V}{dV/dX} \gg D \tag{5}$$

where

V = Voltage
dV/dX = Voltage gradient along the panel
D = Sheath thickness

Using typical values for the SEPS array, Equation (5) requires $D \ll 0.4$ m to be valid. For most of the projected operating conditions, the sheath thickness is substantially larger than 0.4 m leading to appreciable curvature of the particle trajectories. This effect has been verified in testing of the previously mentioned Lockheed flexible solar array panel and in other high voltage tests. In this study, the power loss is calculated based on the panel maximum voltage.

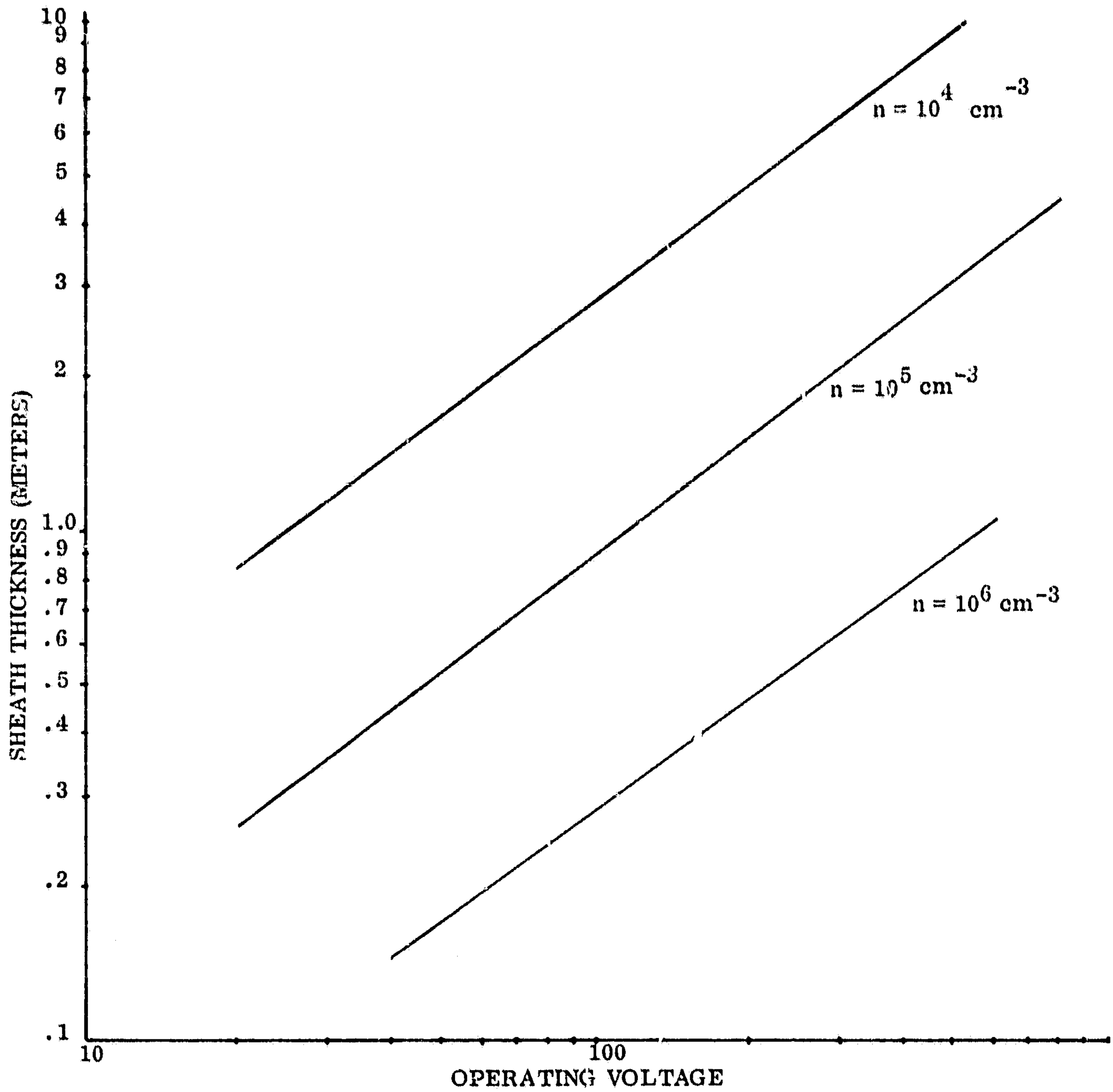


Figure 2-5 Sheath Thickness vs Operating Voltage

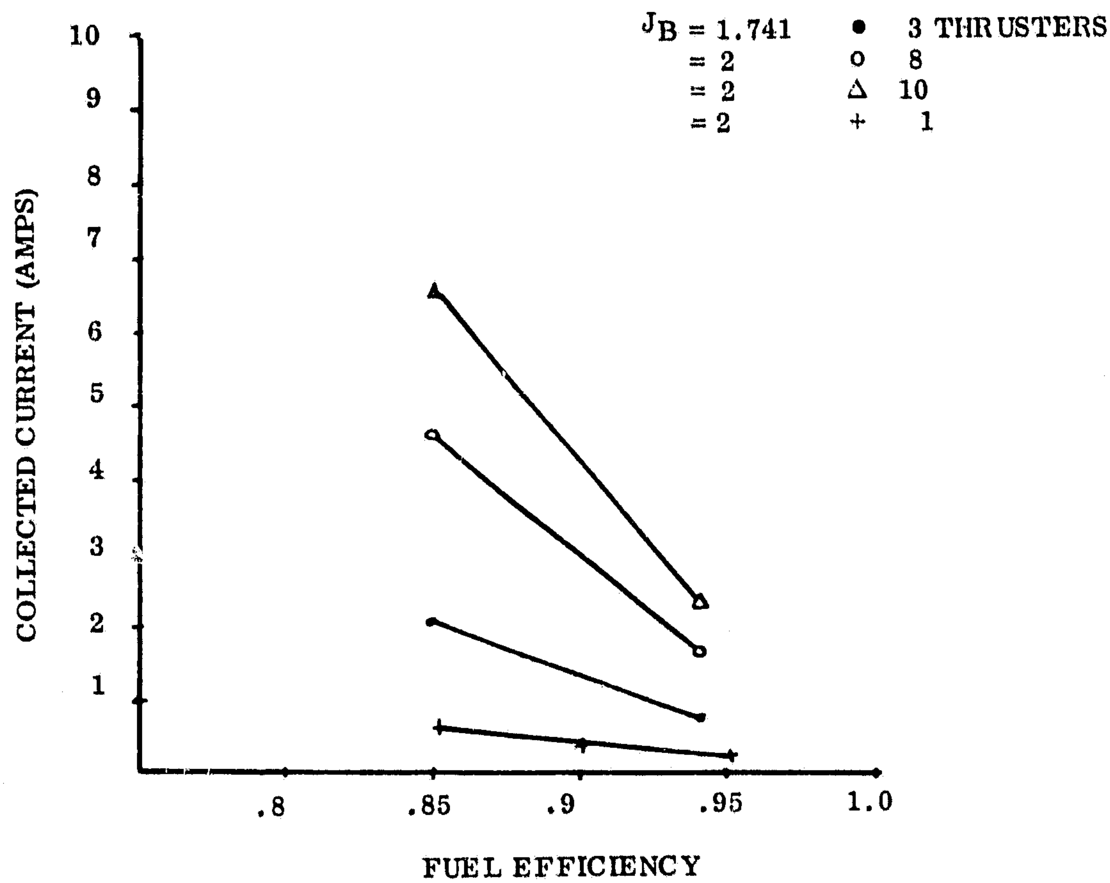
The current collected by the panel was calculated by numerically integrating the current density over the panel area. Power loss is shown in Table 2-1.

The effect of fuel utilization efficiency on current collection was briefly examined with the results shown in Figure 2-6. It is quite clear that operating the thrusters in an inefficient mode will have a major impact on power loss.

The impact on interplanetary missions can be most clearly understood by considering the operation of three interacting thrusters and their associated losses as shown in Table 2-1. One of the desired operating conditions for a proposed Jupiter probe would require the use of three engines at approximately 3 AU. Since this condition would occur after several thousand hours of operation it is reasonable to assume that the efficiency would drop to the 0.85 value listed. Under these conditions the power loss would be so severe, approaching 90%, that the solar array would be unable to provide sufficient power to meet mission requirements.

TABLE 2-1
POWER LOSS ESTIMATES

	Description	J_B (Amps)	η	Power Loss (W) 200 Volts	Power Loss (W) 400 Volts
A	8 Non-Interacting	2	.94	84	--
	8 Interacting	2	.94	664	--
	2 N-I	.5	.81	--	9.6
	2 I	.5	.81	--	19.2
	10 N-I	2	.95	80	--
	10 I	2	.95	800	--
	3 N-I	1.741	.85	--	560
	3 I	1.741	.85	--	1680



*1 WING, CURRENT COLLECTED ON 1 SIDE
NO AREA INCREASE FOR SHEATH GROWTH

Figure 2-6 Current Collection - 1 Wing SEPS S/A
(Interacting Thrusters)

3.0 MODULE DESIGN

3.1 POTENTIAL DESIGN IMPACT

As an outcome of the literature survey and the analysis task, several modifications to the baseline array were suggested and areas where further study is needed were identified. Insulation of exposed conductive surfaces is the obvious first step where feasible. This could include taping the weld access holes. The effects of pinholes cannot at present be quantized. Experimental work has shown a disproportionate amount of current collection and destruction of surrounding and underlying material. The effect of a conductive ground plane surrounding the holes is unknown. It has been pointed out that trajectory effects will be important when the voltage gradient along the plate is similar to the voltage drop through the sheath which should be verified by test.

3.2 ADAPTABILITY

Due to the number of parameters which could affect the interaction of the solar array with the plasma, it was decided early in the program to design the modules to be adaptable. With this philosophy, two modules exemplifying the two major design options--taping the cells to the substrate vs attachment only at the welded interconnects--were planned. Provisions were made to allow systematic modification of these modules to study the loss reduction or gain associated with partial insulation, pin holes, ground planes and total insulation of the array as well as voltage gradients across the sample. The following section will discuss the specific design details incorporated in the samples.

3.3 TEST MODULE OVERVIEW

The two test modules were specified to consist of 36 5.9 x 5.9 cm silicon solar cells mounted to a flexible substrate. The substrate dimension was constrained to be within a 17" x 21" area. The final arrangement selected, shown in Figures 3-1 and 3-2, was a square pattern with the cells lying within a 14.2" x 14.2" area.

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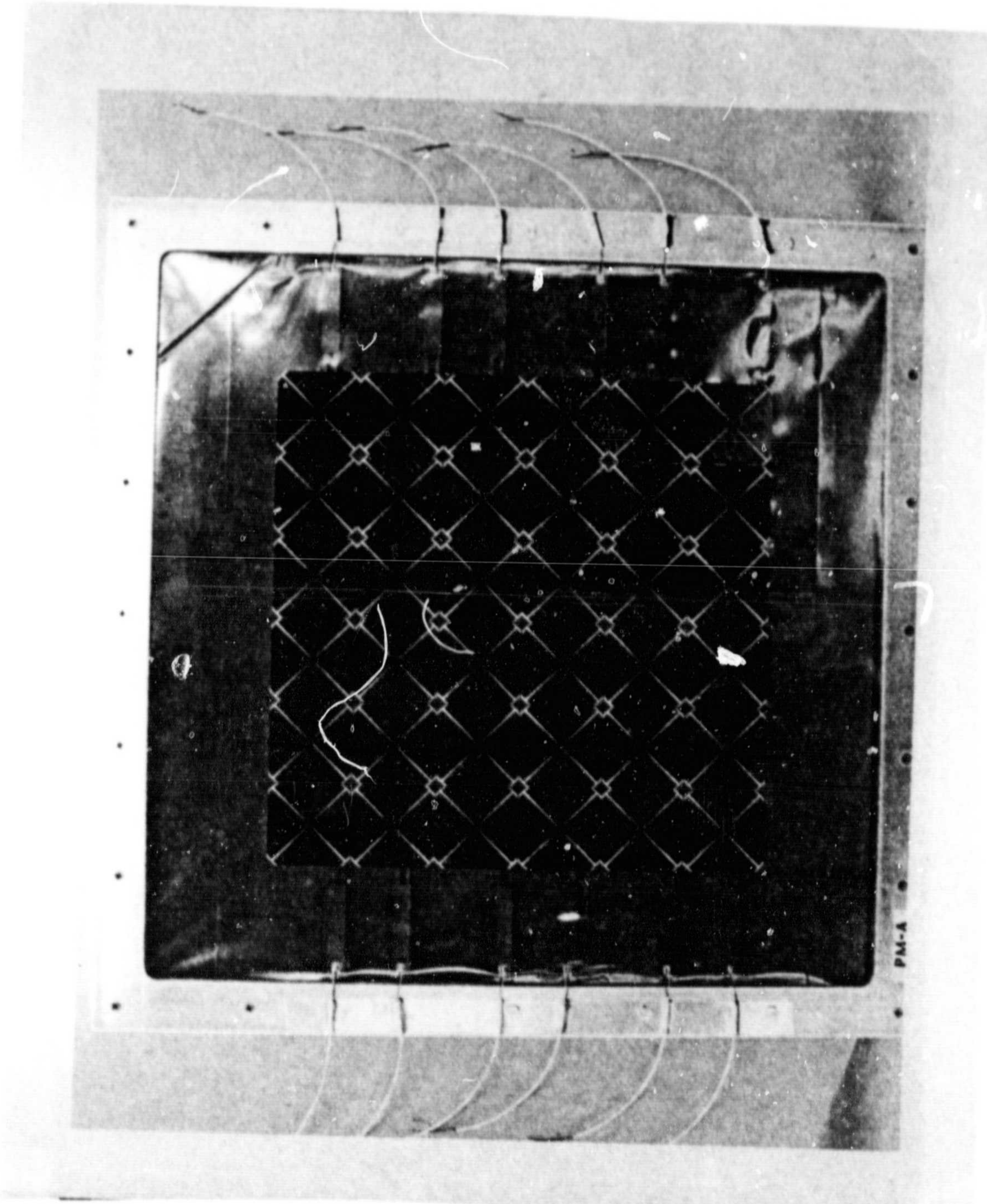

Figure 3-1 (a) Plasma Module A - Front

Figure 3-1 (b) Plasma Module A - Back

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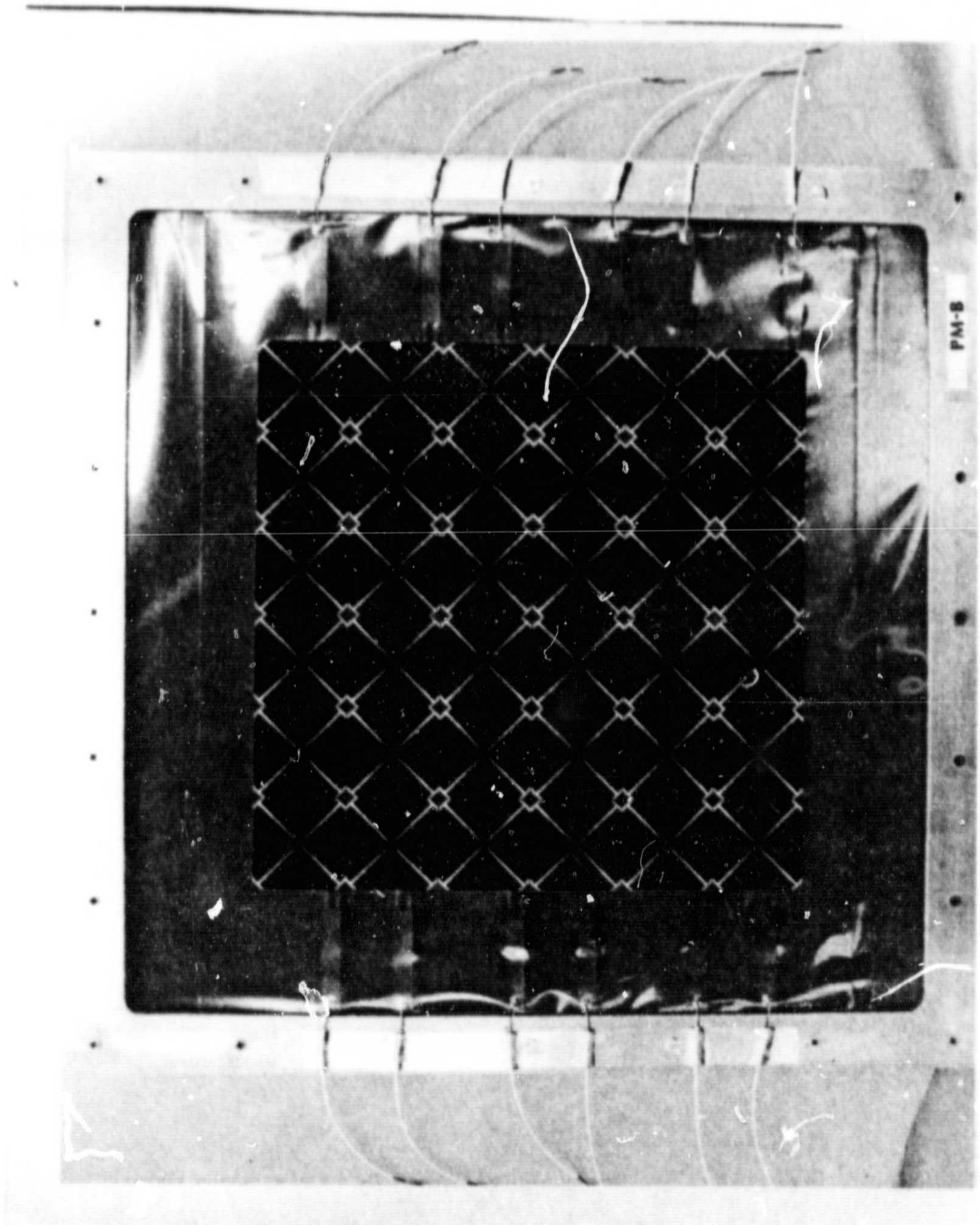

Figure 3-2 (a) Plasma Module B - Front

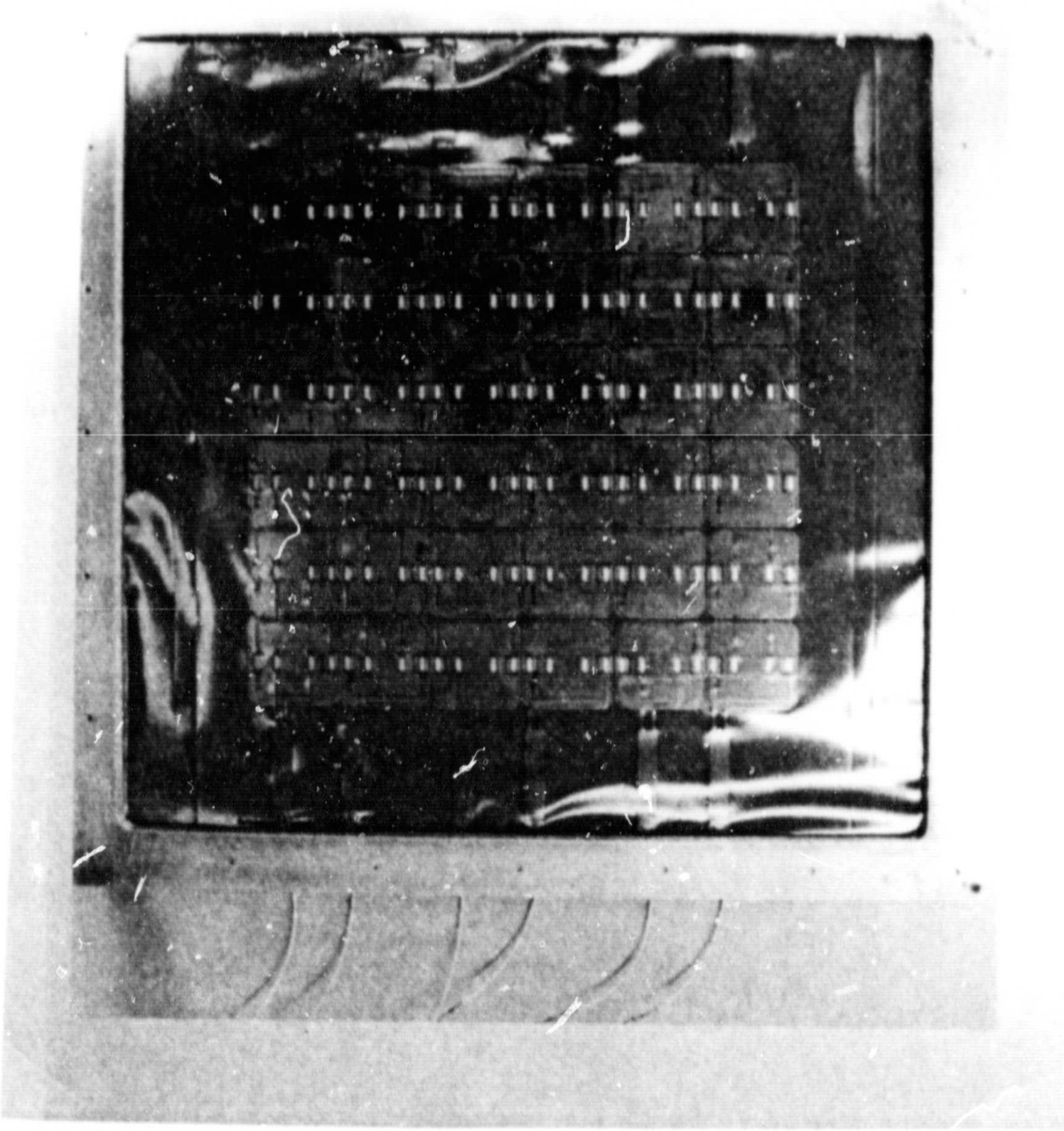

Figure 3-2 (b) Plasma Module B - Back

The square pattern has several desirable features. The diagonal is the shortest length achievable which results in the most uniform light distribution across the sample from a solar simulator. The square pattern also gives rise to the largest number of series-parallel wiring options (Figure 3-3). In addition, it has the largest number of cells in the center section surrounded by other cells. This allows the outer strings to be wired as a crude guard ring, if desired, to study edge effects.

3.4 ELECTRICAL PERFORMANCE

Each cell used in these modules was individually I-V tested prior to installation on the substrate as a diagnostic aid in event of a failure during testing. A cell identification map showing code number, location and string number for each module are shown in Figures 3-4 and 3-5. Due to the large number of individual curves, they are not included in this report but will be provided on request. I-V curves for each string are shown in Figures 3-6 through 3-17.

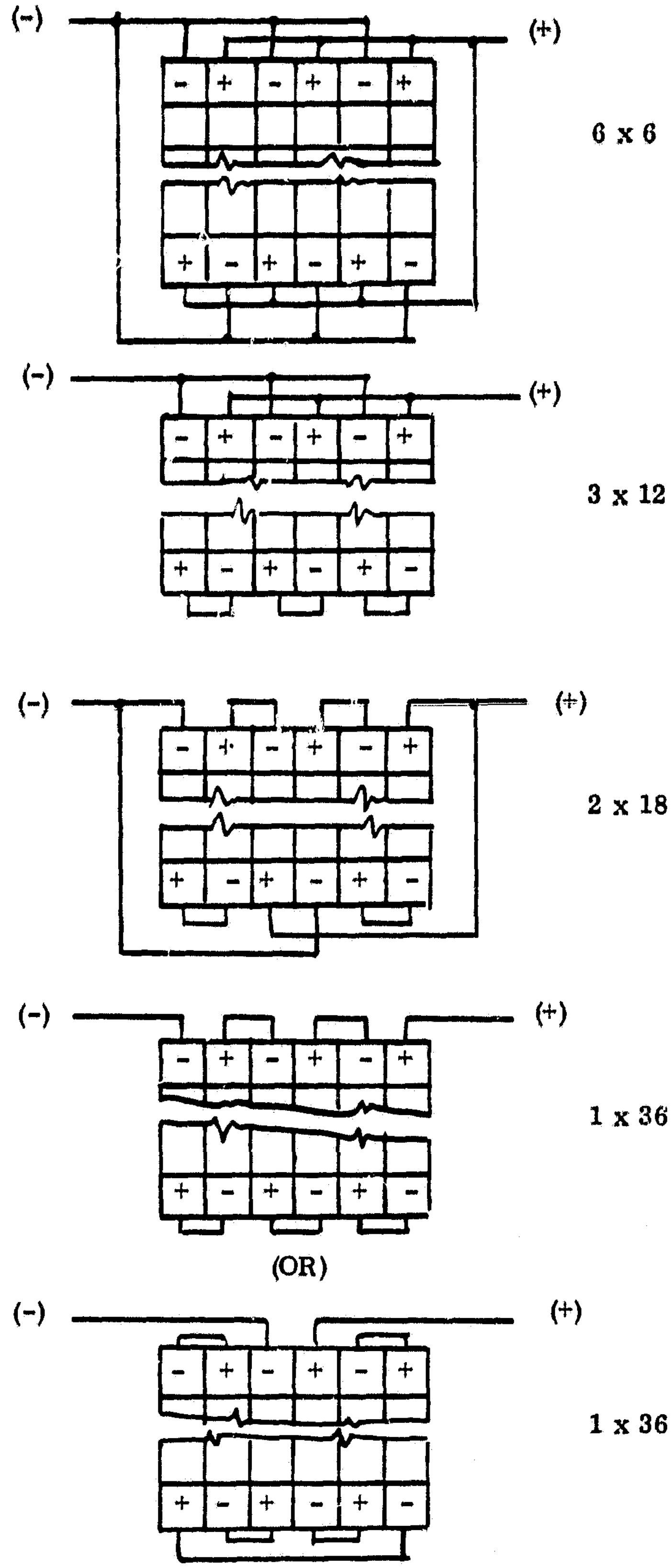

Figure 3-3 Wiring Schematics for Series-Parallel Options

VIEW FROM BACK OF PANEL

707	713	833	825	819	701
708	801	834	827	820	702
709	802	836	828	821	703
710	803	837	829	822	704
711	M701	838	830	823	705
712	M702	839	831	824	706
(6)	(5)	(4)	(3)	(2)	(1)

Figure 3-4 Module A - Cell Identification No. Location Diagram

VIEW FROM BACK OF PANEL

807	913	901	1001	907	813
808	914	902	1002	908	814
809	915	903	1003	909	815
810	804	904	1004	910	816
811	805	905	1005	911	817
812	806	906	916	912	818
(1)	(2)	(3)	(4)	(5)	(6)

Figure 3-5 Module B - Cell Identification Number Location Diagram

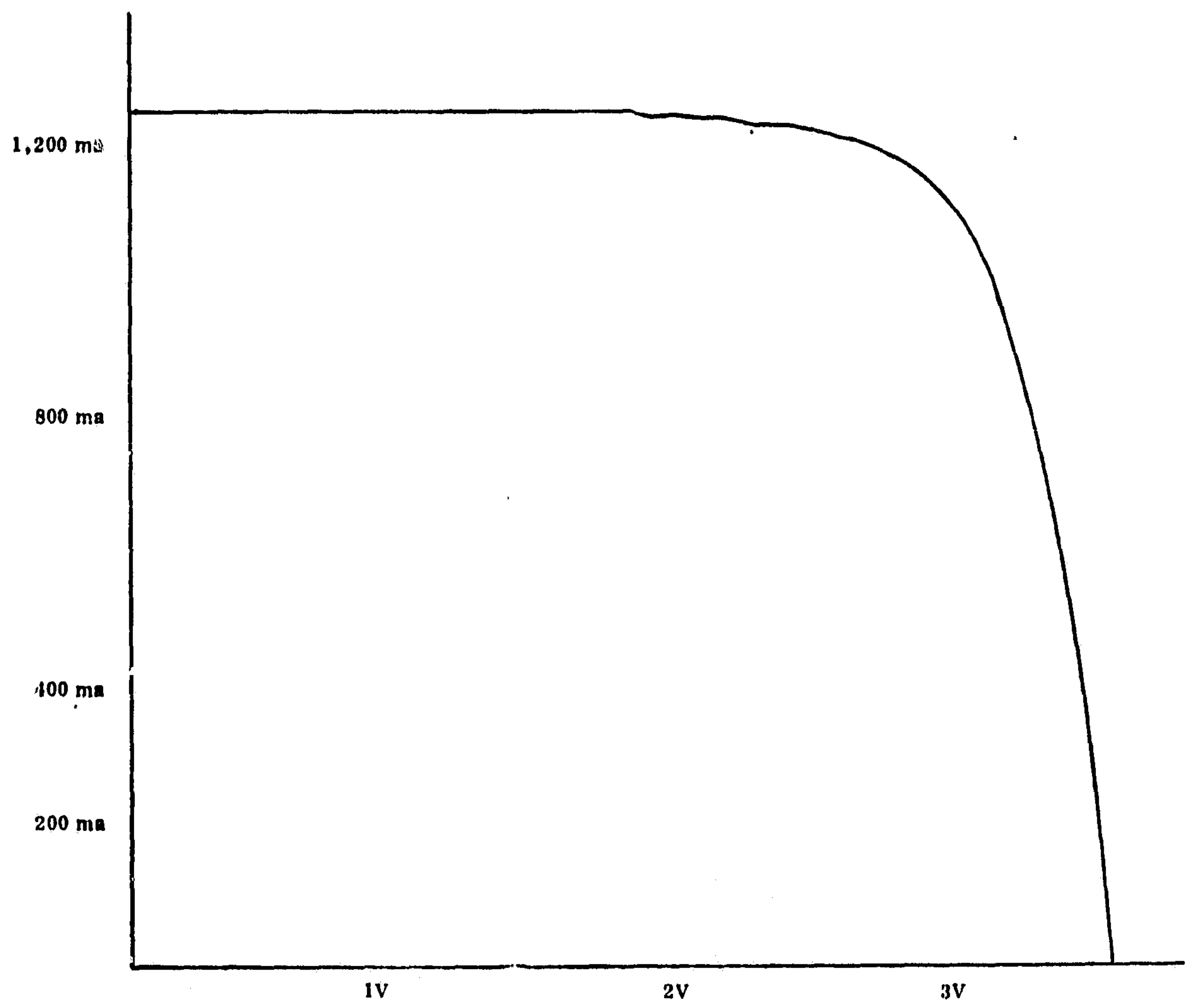

Figure 3-6 Electrical Performance Characteristics PM-A Group 1

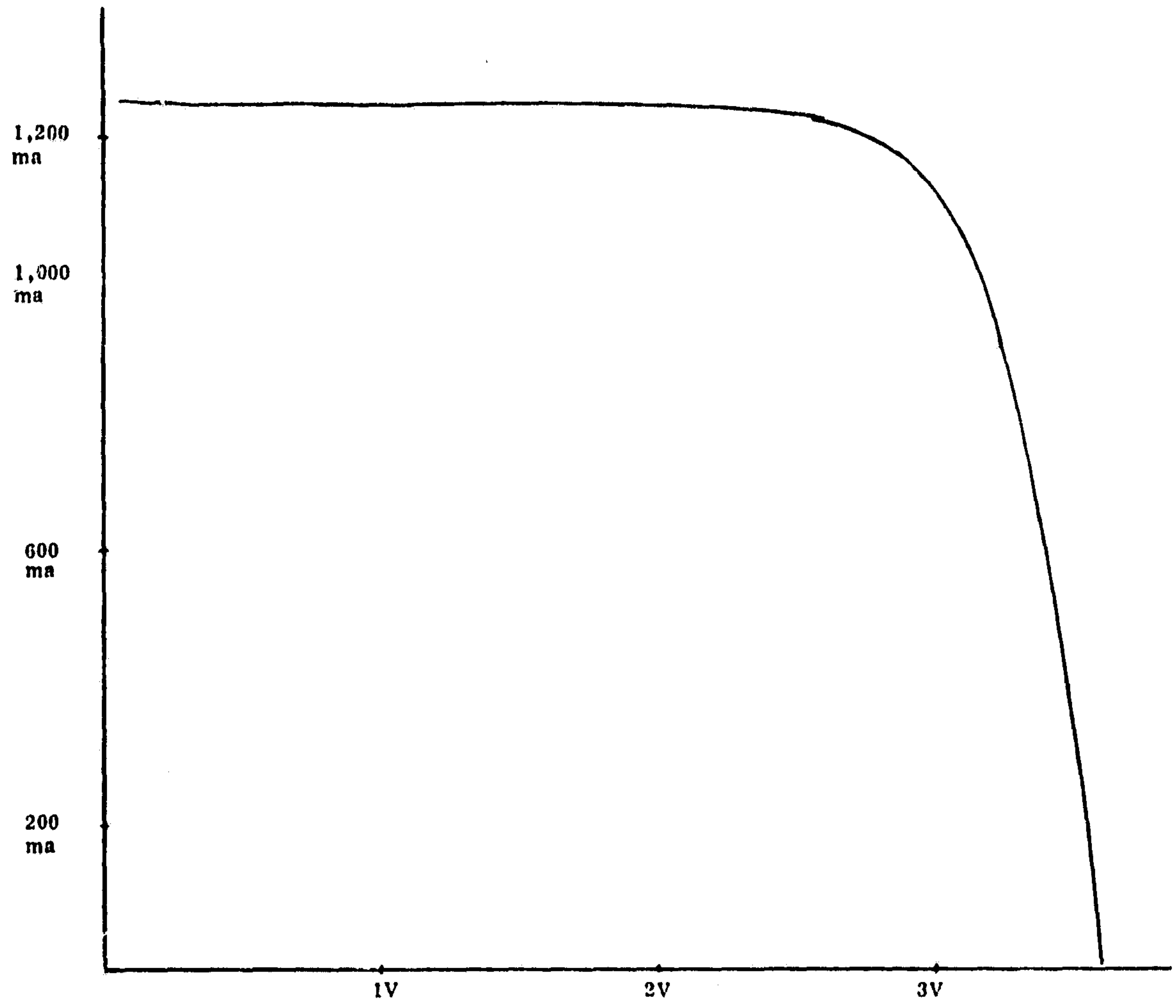

Figure 3-7 Electrical Performance Characteristics
PM-A Group 2

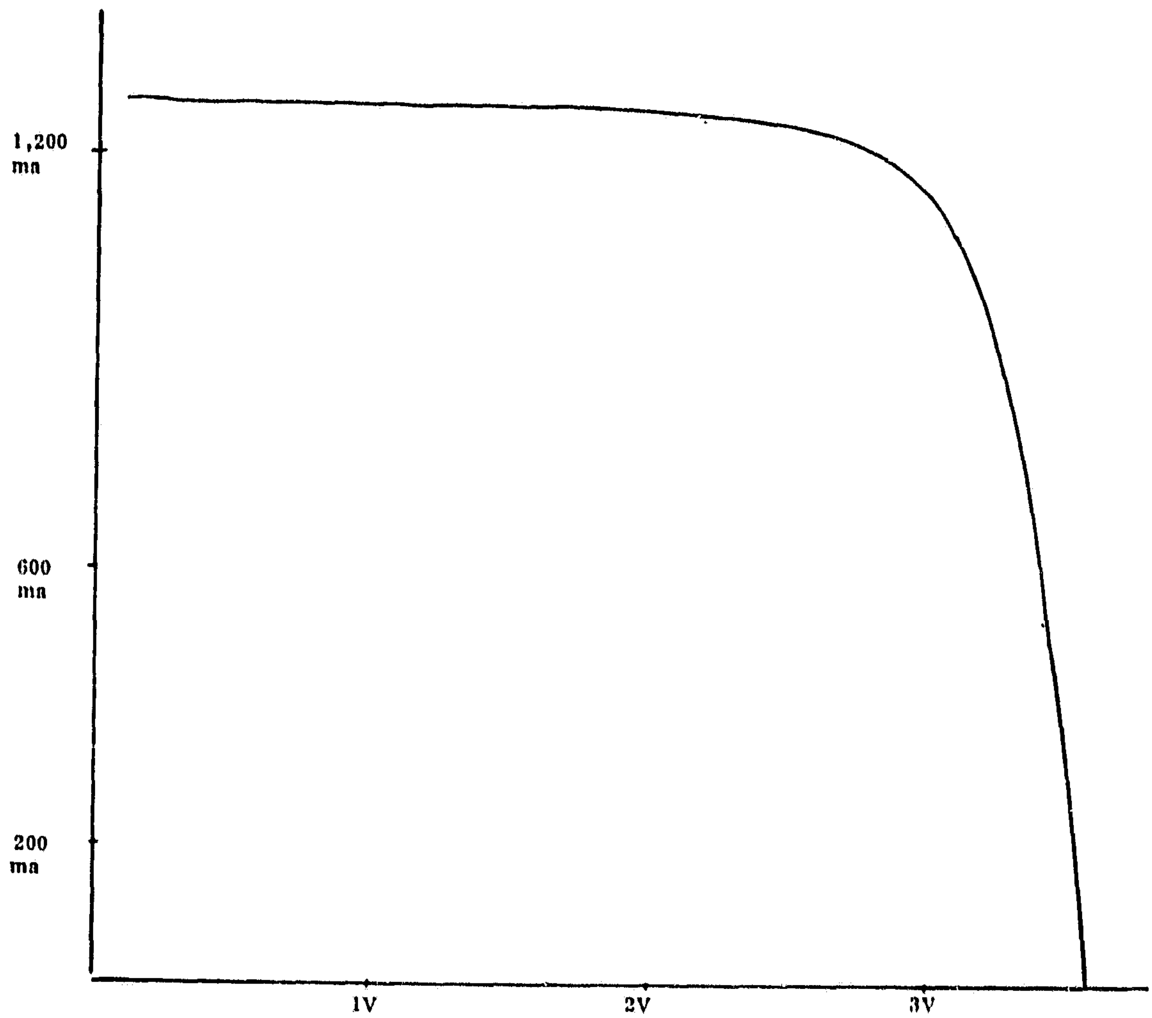

Figure 3-8 Electrical Performance Characteristics
PM-A Group 3

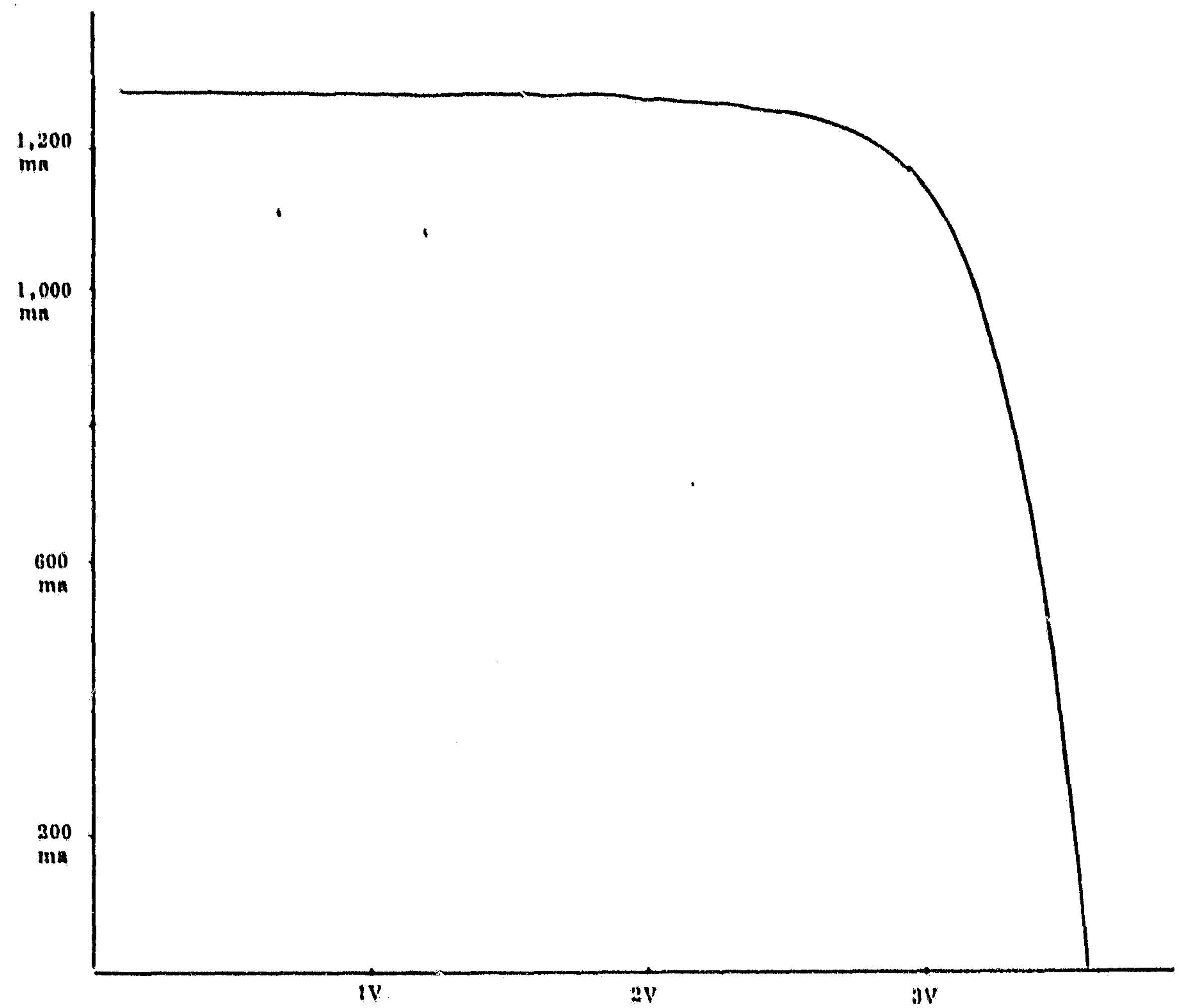

Figure 3-9 Electrical Performance Characteristics
PM-A Group 4

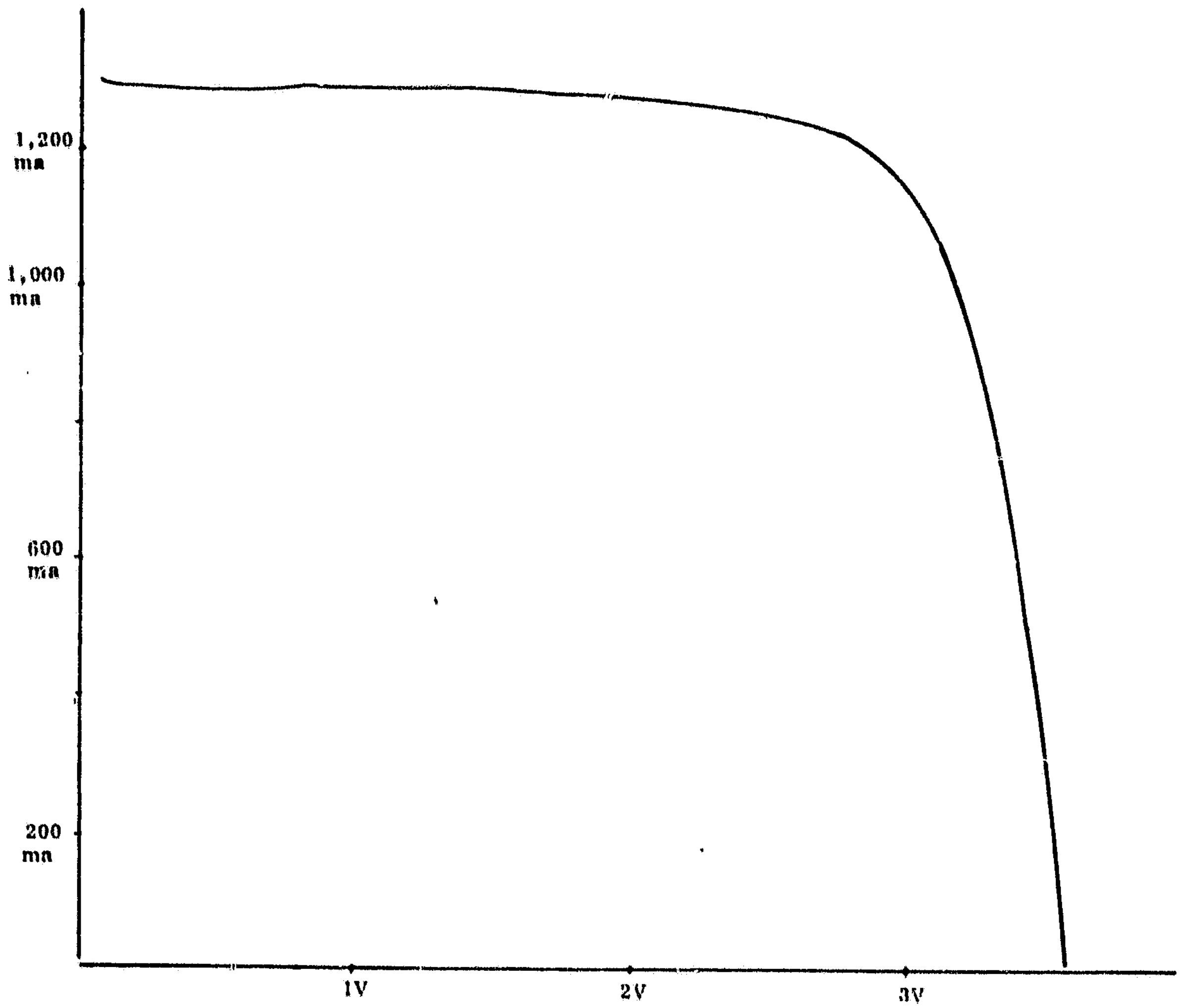

Figure 3-10 Electrical Performance Characteristics
PM-A Group 5

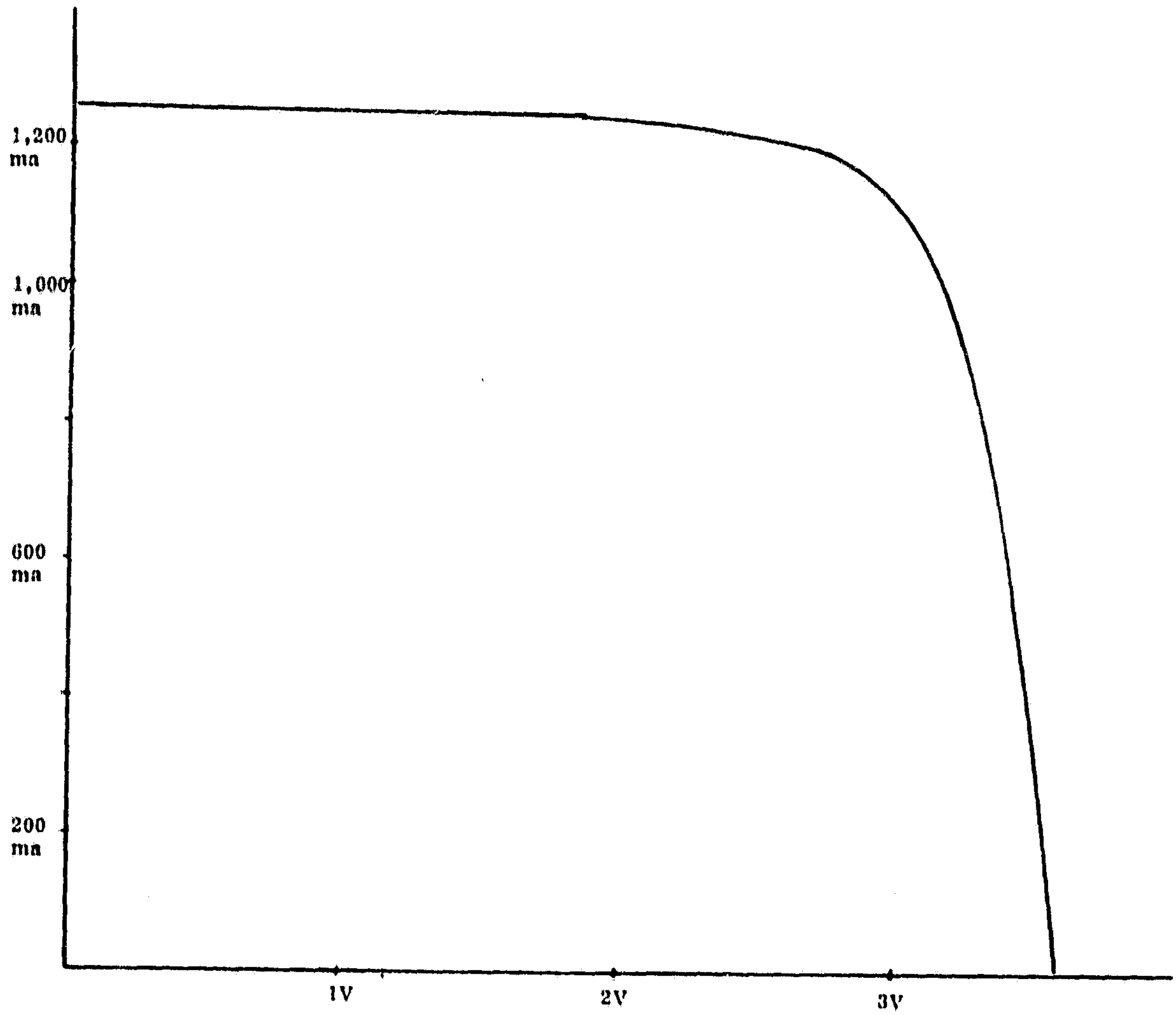

Figure 3-11 Electrical Performance Characteristics
PM-A Group 6

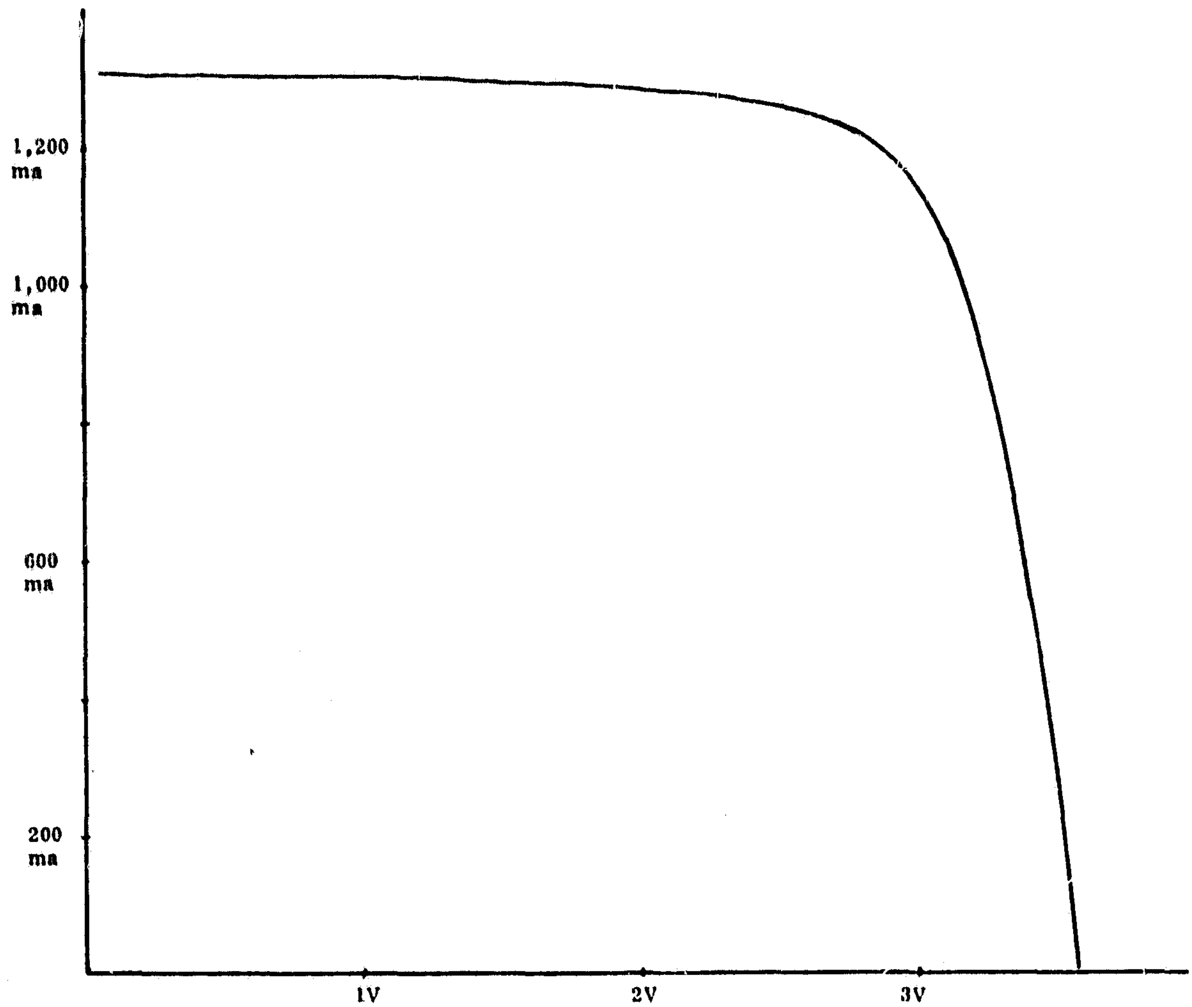

Figure 3-12 Electrical Performance Characteristics
PM-B Group 1

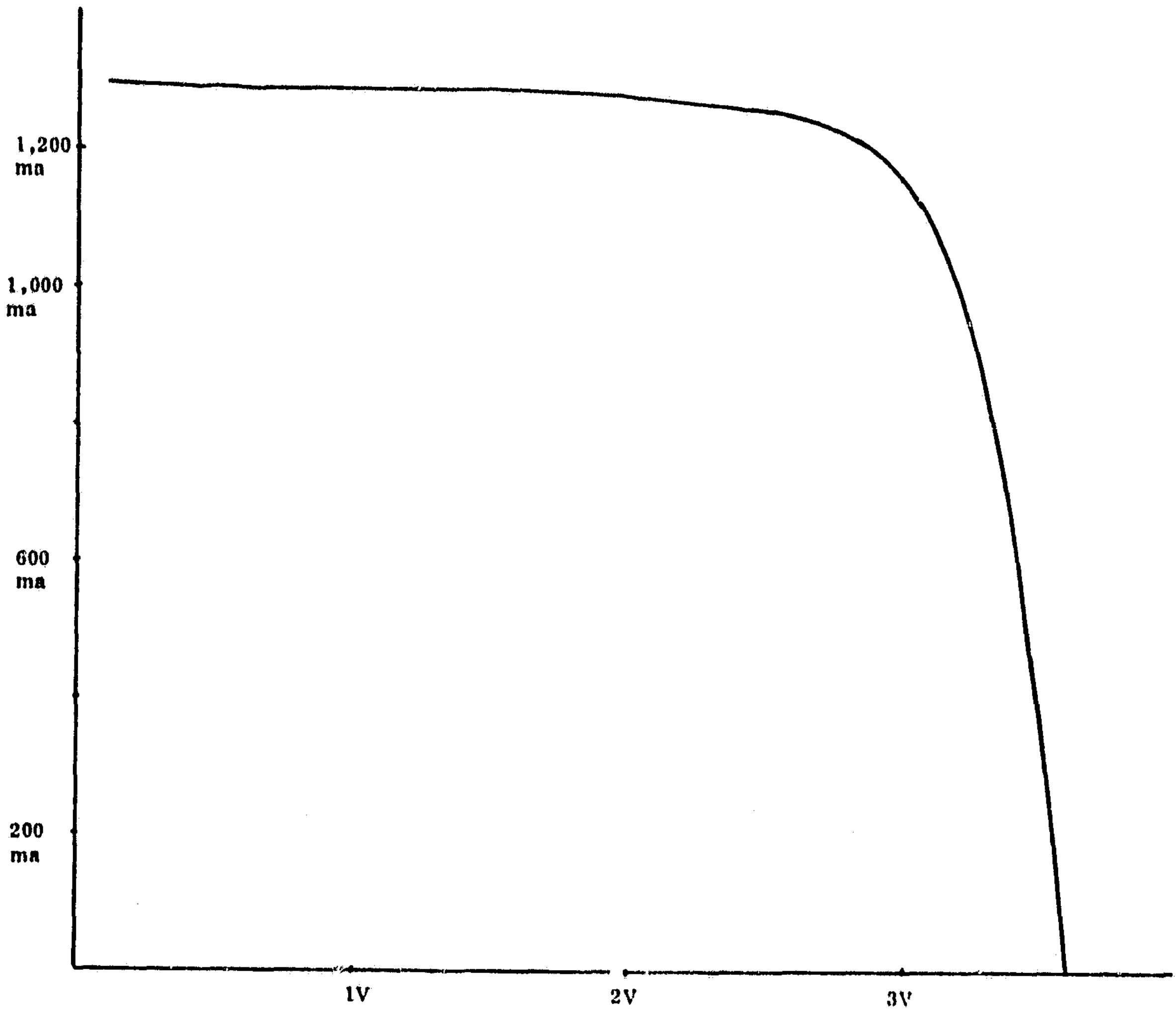

Figure 3-13 Electrical Performance Characteristics
PM-B Group 2

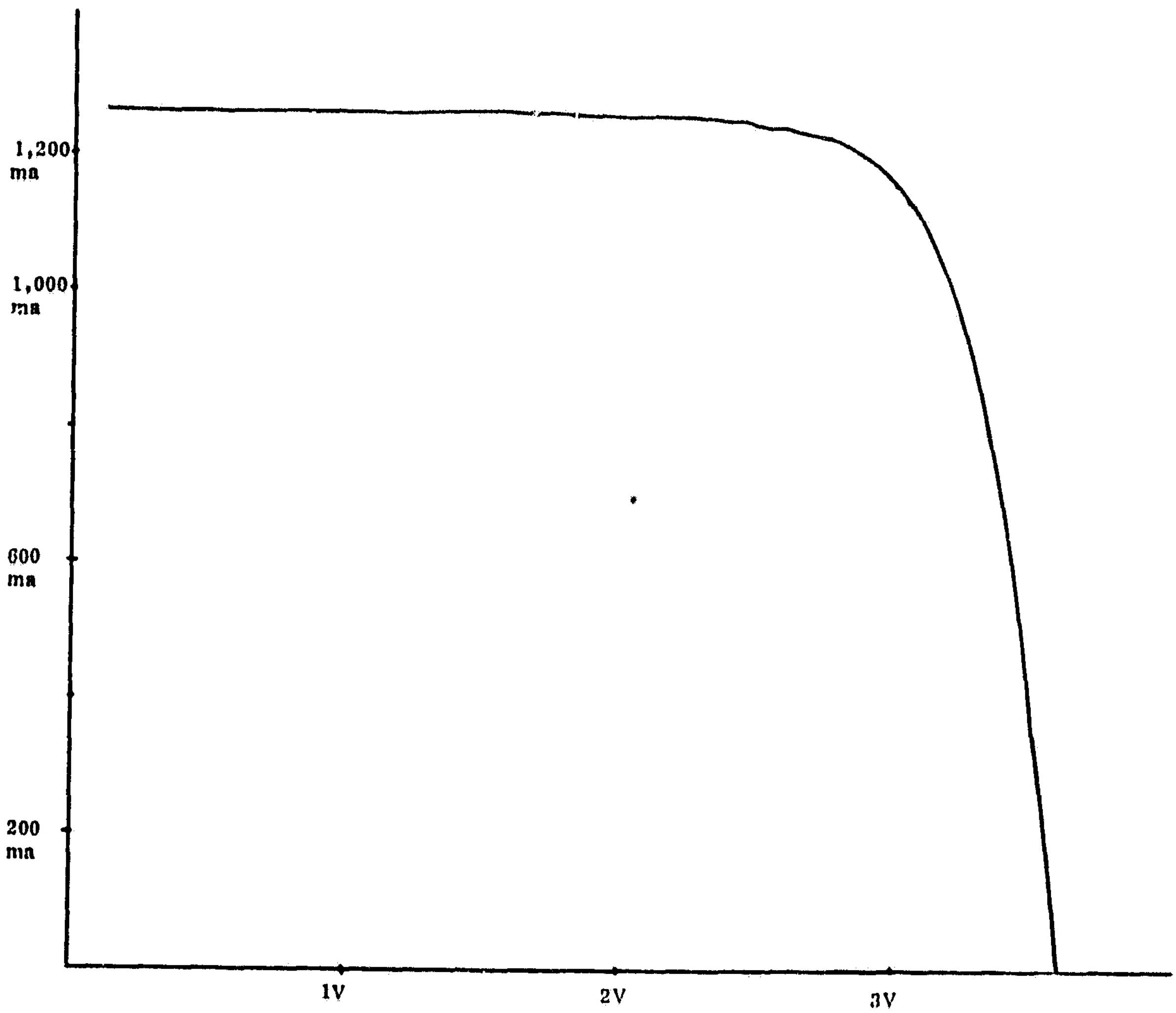

Figure 3-14 Electrical Performance Characteristics
PM-B Group 3

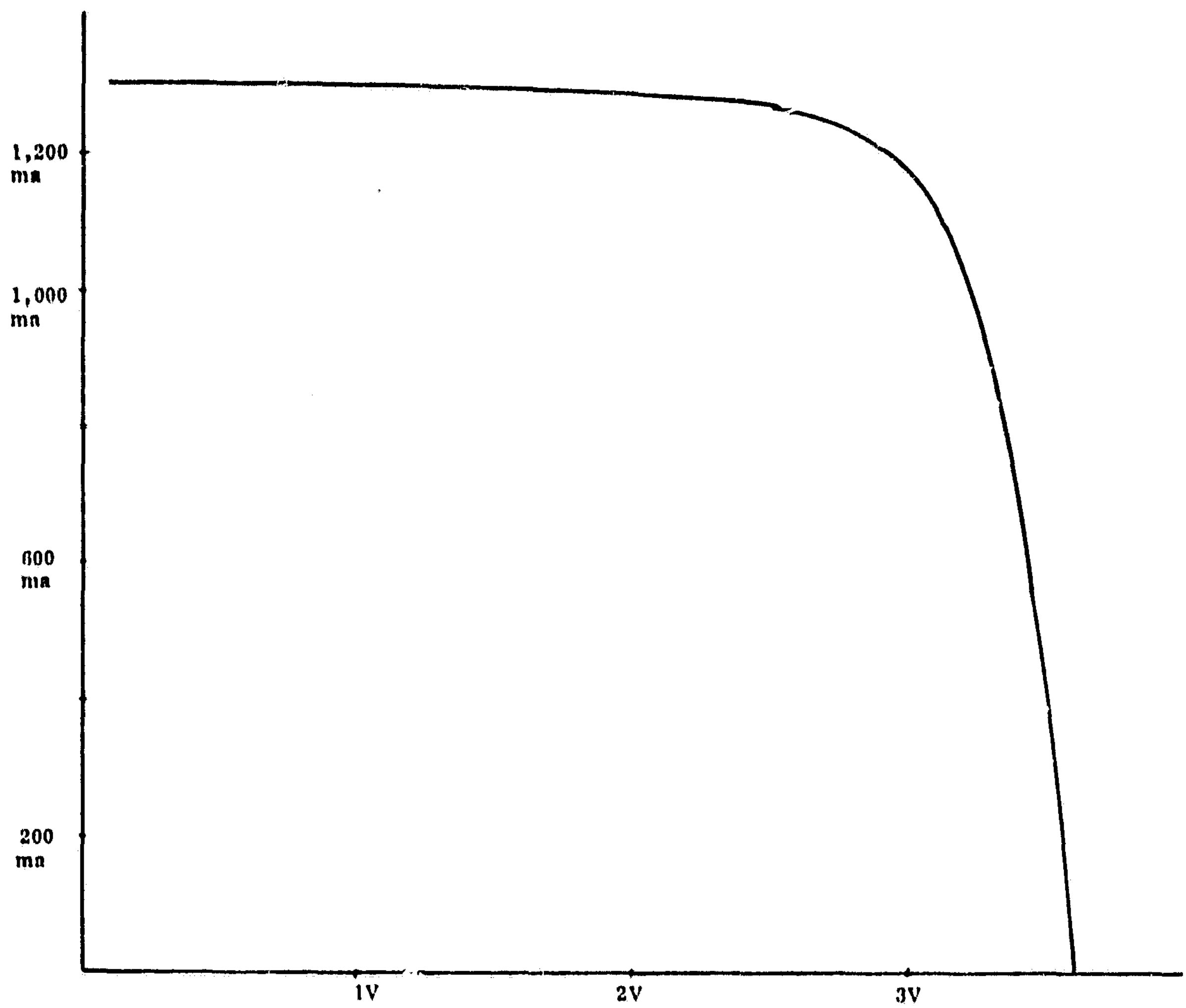

Figure 3-15 Electrical Performance Characteristics
PM-B Group 4

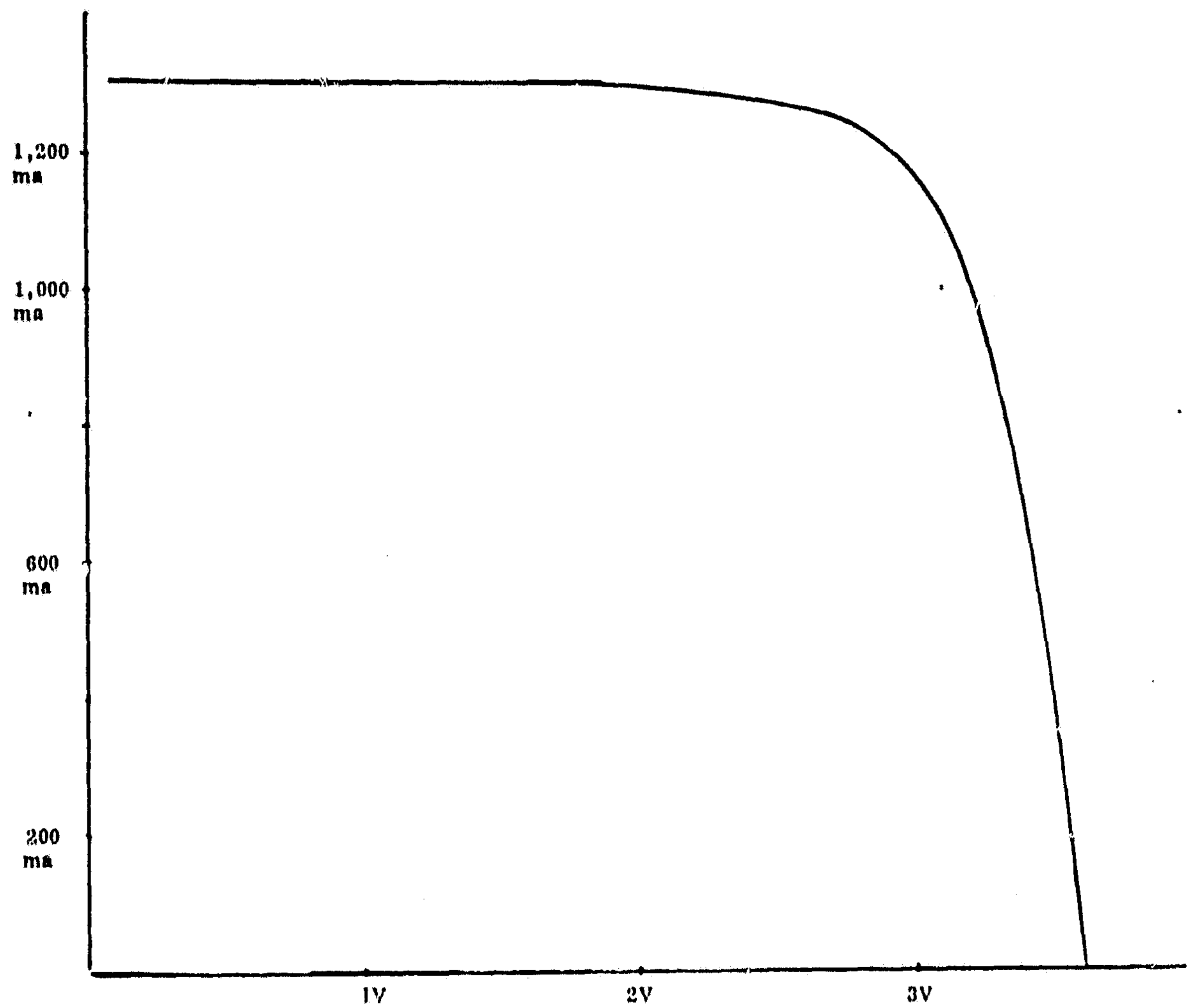

Figure 3-16 Electrical Performance Characteristics
PM-B Group 5

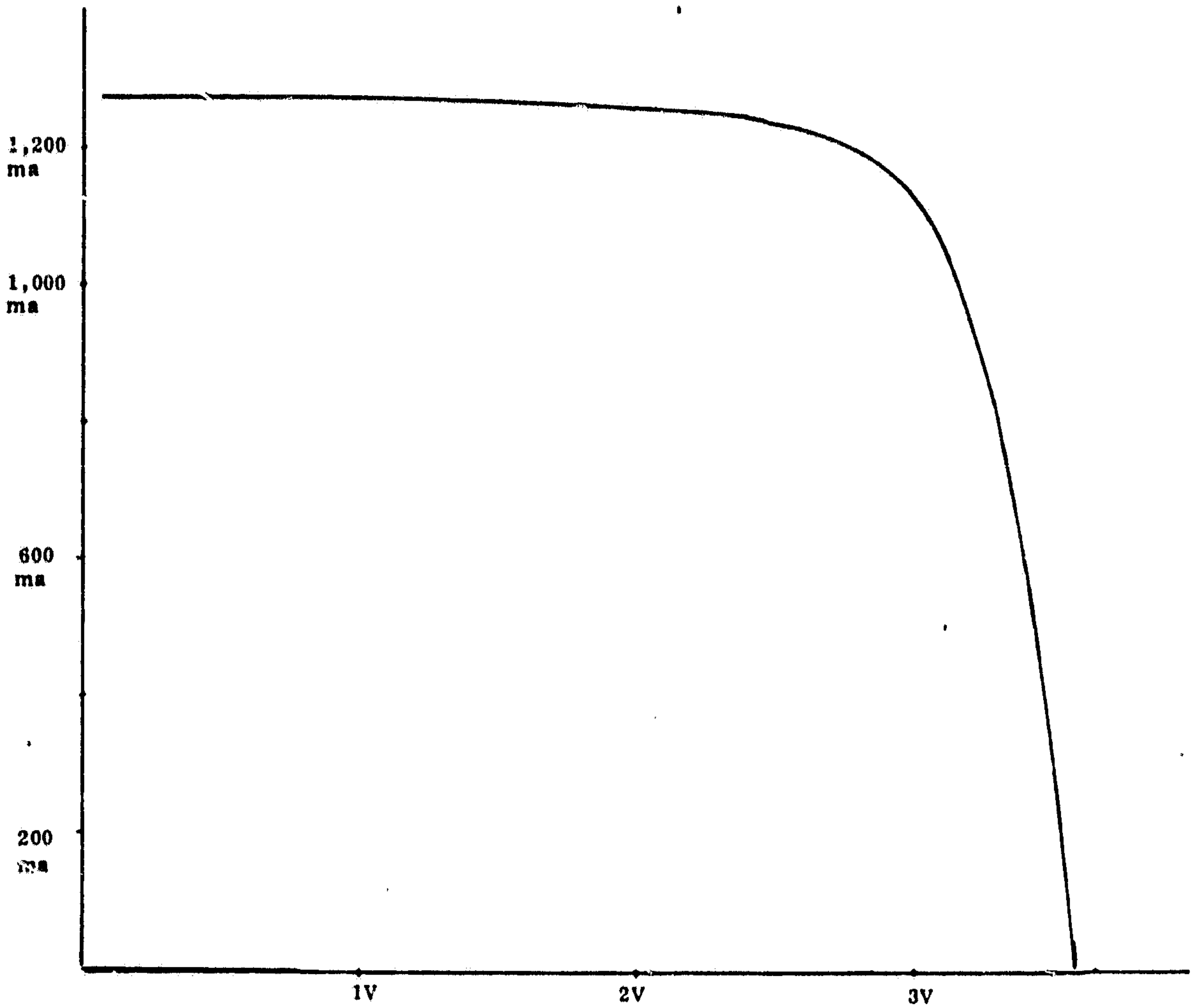

Figure 3-17 Electrical Performance Characteristics
PM-B Group 6

4.0 SUMMARY

In support of the SEPS Program, this study was to briefly examine analytically the effects of a large high voltage solar array interacting with an ion thruster produced plasma. Conclusions reached during the analytical portion of this effort were to be translated into design modifications which would then be incorporated into two test modules, one of which would use conventional construction practices while the other would incorporate those features which would minimize the interactive effects between plasma and solar array.

During the course of a brief literature survey and subsequent analysis, several physical processes which are not fully understood were encountered. The test module design philosophy was therefore modified to provide two modules which were adaptable to investigate the effects of several design options and gain a basic understanding of plasma interaction with solar arrays.

Two modules consisting of 36 large area 5.9 cm x 5.9 cm wraparound contact solar cells welded to a flexible Kapton integrated circuit substrate were fabricated. These modules contain features to allow an experimental evaluation of the effects of insulation, pin-holes, bonding the cell to the substrate and a ground plane. Pre-test I-V measurements were made on all cells used in the array and upon each of the final strings. The modules were delivered to NASA's Lewis Research Center where they are currently undergoing plasma testing.

5.0 RECOMMENDATIONS

As solar arrays get larger and generate more power, the impetus to go to higher voltages to reduce cabling and converter weight will gain more support. There are currently under study several missions where solar arrays would be required to generate hundreds of kilowatts in low earth orbit. These include space power platforms which would operate in regions where the plasma density could exceed 10^6 cm^{-3} while operating at voltages in excess of 400 volts. In order to realistically assess the performance potential of these systems, the question of the magnitude of the power loss associated with plasma interaction must be answered.

The following areas require specific attention in order to support planning and design of missions utilizing high voltage solar arrays.

Testing of the modules fabricated under this contract will provide data on the effects of pin-holes, insulation and ground planes. In order to properly understand the test results, an analytical effort to model the collection mechanisms and remove test effects is necessary. This modelling effort should proceed from an appreciation of the basic physics and geometry of the test set-up.

Future testing and modelling should also concentrate on understanding the effects associated with size and shape of the array. Testing to date has been insufficient to illuminate the basic scaling relationships involved. Since the size of future arrays precludes the possibility of ground testing, the effect of changes in scale and aspect ratio needs to be well understood to allow accurate projection of test results to these larger arrays.

An accurate, cost effective, system level, analytical modelling capability to examine the interactive effects of vehicle and solar array needs to be developed. Current models are costly, complex, optimized for synchronous application and not very accurate. They were primarily developed to study charging at synchronous and will not handle the high density LEO case.

These efforts are necessary to support the design process and developmental flight testing.

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APPENDIX A

This appendix is intended to present a summary of the results of a literature survey undertaken early in the contract period to identify potential problems, test data, flight experience and design modifications which could be incorporated in the design of two solar array test modules. Relevant literature is cited in Table A-1 with the date, type (experimental or theoretical), and data source (ground test or flight) where necessary.

TABLE A-1

SOLAR ARRAY/PLASMA INTERACTION DATA BASE

Ref. No.	Date	Ion Thruster Plume	High Voltage S/A	Leakage Current	Pinholes	S/C Potential
31	81	T				
3	80		T, GT	T		
9	80		GT, T	GT, T		
12	80		T	T		
A						
1	79	T				
25	79			GT, T	GT, T	
32	79	T	T			
33	79	FT				
30	79	T				
2	78	R				
7	78					T
8	78					GT
11	78	T	T	T		
13	78		GT	GT, T		
15	78			GT, T		
16	78		T	T		
17	78		T	T		
18	78		T	T		
19	78		T	T		
20	78		T	T		
21	78	T	T	T		
5	77					T
6	77					T
22	76	T, GT	T	T		
23	76	T				
14	75					T, FT
12	74		GT, T	GT, T	GT	
B						
10	72		T, GT	GT	GT	
28	72			T		
4	70	T	T	T		
26	70		T	T		
27	70	T	T	T		
29	69			GT		
A						
34	80	GT				
35	80	GT				
37	80	T				
B						
36	74		GT	GT	GT	GT
C						
39	24			T		
38	23			T		

T = Theoretical/Analytical　　FT = Flight Test
GT = Ground Test　　R = Review